IC 8919

Bureau of Mines Information Circular/1983

Guidelines for Siting Product-of-Combustion Fire Sensors in Underground Mines

By C. D. Litton

UNITED STATES DEPARTMENT OF THE INTERIOR

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James G. Watt, Secretary

BUREAU OF MINES
Robert C. Horton, Director

This publication has been cataloged as follows:

Litton, C. D. (Charles D.)

Guidelines for siting product-of-combustion fire sensors in underground mines.

(Information circular / United States Department of the Interior, Bureau of Mines ; 8919).

Includes bibliographical references.

Supt. of Docs. no.: I 28.27:8919.

1. Mine fires—Prevention and control. 2. Fire detectors—Location. 3. Combustion gases. I. Title. II. Series: Information circular (United States. Bureau of Mines) ; 8919.

TN295.U4 [TN315] 622s [622'.8] 82-600343

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GUIDELINES FOR SITING PRODUCT-OF-COMBUSTION FIRE SENSORS IN UNDERGROUND MINES

By C. D. Litton[1]

ABSTRACT

This Bureau of Mines report presents a set of guidelines for determining the distribution of product-of-combustion fire sensors in underground mines. Sensor spacing is defined in terms of sensor alarm threshold, ventilation flow rate, and mine entry dimensions. Sensor spacing guidelines are presented for detection of fires from two primary combustibles, coal and wood, which are common to the majority of underground mines. The guidelines are based on data from full-scale and intermediate-scale fire tests conducted by the Bureau of Mines.

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INTRODUCTION

A major goal of the Bureau of Mines safety research program is to improve the degree of safety afforded underground miners. Rapid and reliable detection of mine fires can contribute to this goal by improving miners' chances for escape during actual fire emergencies.

It is apparent that the use of sensitive and reliable product-of-combustion (POC) fire sensors in underground mines is increasing, owing primarily to the greater availability of such sensors, as well as an added awareness of the need for rapid and reliable underground fire detection systems. As the use of such sensors grows, the required distribution of these sensors within mine entries will need to be determined in order to provide realistic and adequate fire detection. Previous Bureau reports[2] have discussed this problem and outlined the various parameters involved.

This report summarizes the previous data and presents subsequent guidelines for determining POC fire sensor distributions within mine entries. These guidelines may be easily used by those responsible for either designing or approving the design of POC fire detection systems in underground mines.

It is not the intent of this report to suggest or recommend specific fire sensors or sensing systems. Rather, the report proposes a strategy for determining the most effective distribution of whatever sensors are selected. It is important that one using these guidelines know in advance the type of sensor to be used and its characteristics.

SPACING AND SITING GUIDELINES

For convenience, the spacing and siting guidelines for POC fire sensors in underground mines are presented first, along with instructions for their general use. Explanatory material, on which the guidelines are based, can be found in the sections that follow.

SPACING

To determine the appropriate spacing between POC fire sensors within a mine entry, these steps should be followed:

1. Determine the average entry height (H) and width (W).

2. Take the ratio of height to width (H/W) and, from figure 1, determine the appropriate value for the entry parameter (γ_E).

3. Determine the type of sensor to be used (CO, CO_2, or smoke) and its alarm threshold (X_a); that is, the POC concentration that will activate the sensor alarm.

4. Determine the primary combustible within the entry (either coal or wood) and, from table 1, select the production constant (K_x) for the product to be detected.

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[2]Litton, C. D. Product-of-Combustion Fire Detection in Mines. Paper in Underground Metal and Nonmetal Mine Fire Protection. Proceedings: Bureau of Mines Technology Transfer Seminars, Denver, Colo., Nov. 3, 1981, and St. Louis, Mo., Nov. 6, 1981. BuMines IC 8865, 1981, pp. 28-48.

Litton, C. D., M. Hertzberg, and A. L. Furno. Fire Detection Systems in Conveyor Belt Haulageways. BuMines RI 8632, 1982, 26 pp.

_____. The Growth, Structure, and Detectability of Fires in Mines and Tunnels. Proc. 18th Internat. Symp. on Combustion, Waterloo, Ontario, Canada, Aug. 17-25, 1980. The Combustion Institute, Pittsburgh, Pa., 1981, pp. 633-639.

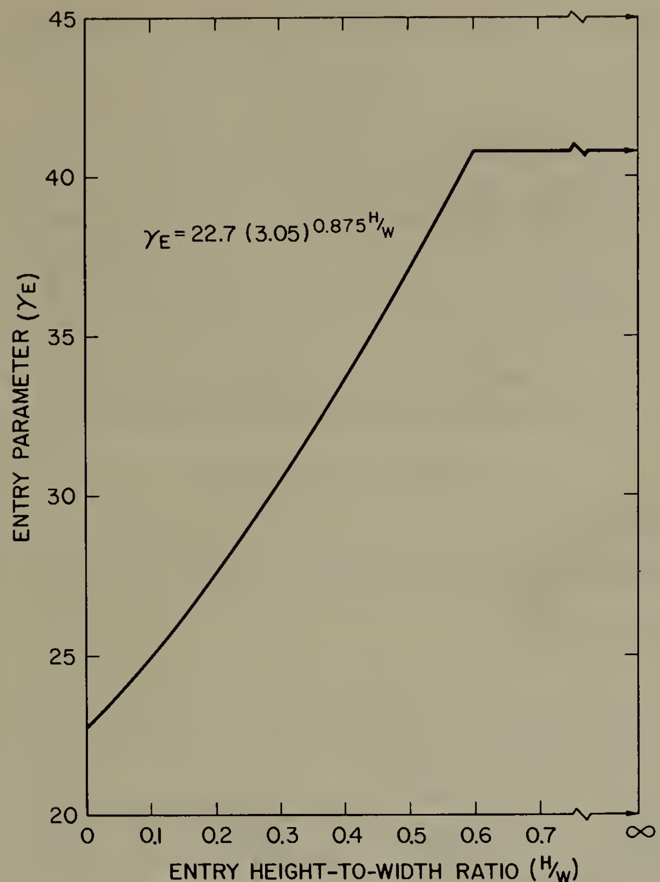

FIGURE 1. - Entry parameter (γ_E) as a function of the entry height-to-width ratio (H/W).

TABLE 1. - Production constants for coal and wood

K_x[1]	POC concentration units	Coal	Wood
K_{CO}	ppm..........	1.10	0.95
K_{CO_2}	ppm..........	6.70	6.90
K_{SMP}	particles per cm^3.	7.2×10^4	2.5×10^5
K_{SMP}	mg/m^3........	0.45	0.30

SMP Smoke particles.
[1]Subscript indicates sensor type.

5. Determine (or estimate) the average background level (X_o) of the product to be detected.

6. Subtract X_o from X_a and divide the result by the appropriate K_x-value.

7. From figure 2, determine the value of the POC parameter (γ_x) at the value of $\frac{X_a - X_o}{K_x}$ defined in step 6.

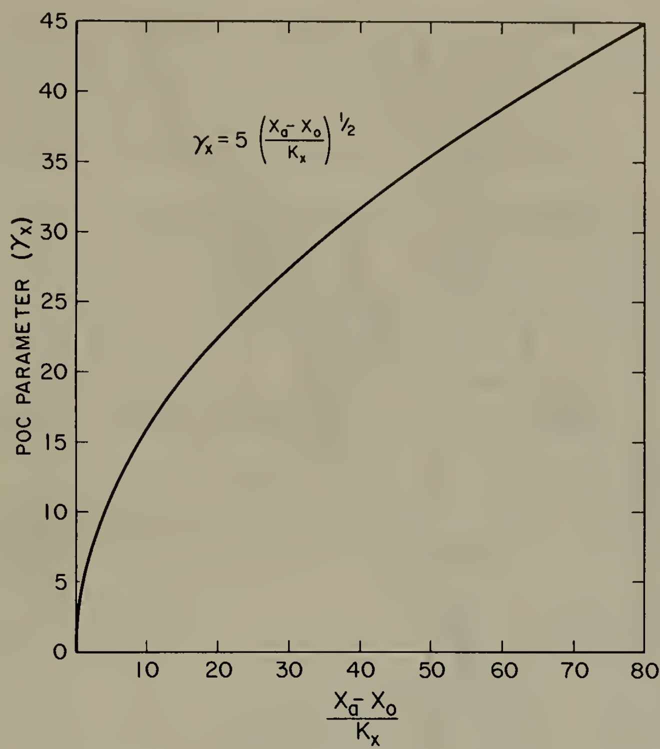

FIGURE 2. - POC parameter (γ_x) as a function of the ratio of alarm threshold to production constant [$(X_a - X_o)/K_x$].

8. Determine the average ventilation velocity (v_f), in feet per minute, within the entry and, in figure 3, draw a vertical line at this velocity parallel to the y-axis.

9. Multiply H by W to determine the average entry cross-sectional area (A) and, in figure 3, draw a horizontal line at this A-value parallel to the x-axis.

10. The point of intersection of the vertical and horizontal lines in figure 3 defines the appropriate spacing category to be used for this entry, and the appropriate spacing equation.

For illustrative purposes, consider the following example.

1. H = 6 ft; W = 20 ft.

2. From figure 1, at H/W = 6/20 = 0.3, γ_E = 30.4.

3. Sensor type: CO; alarm threshold (X_a) = 20 ppm.

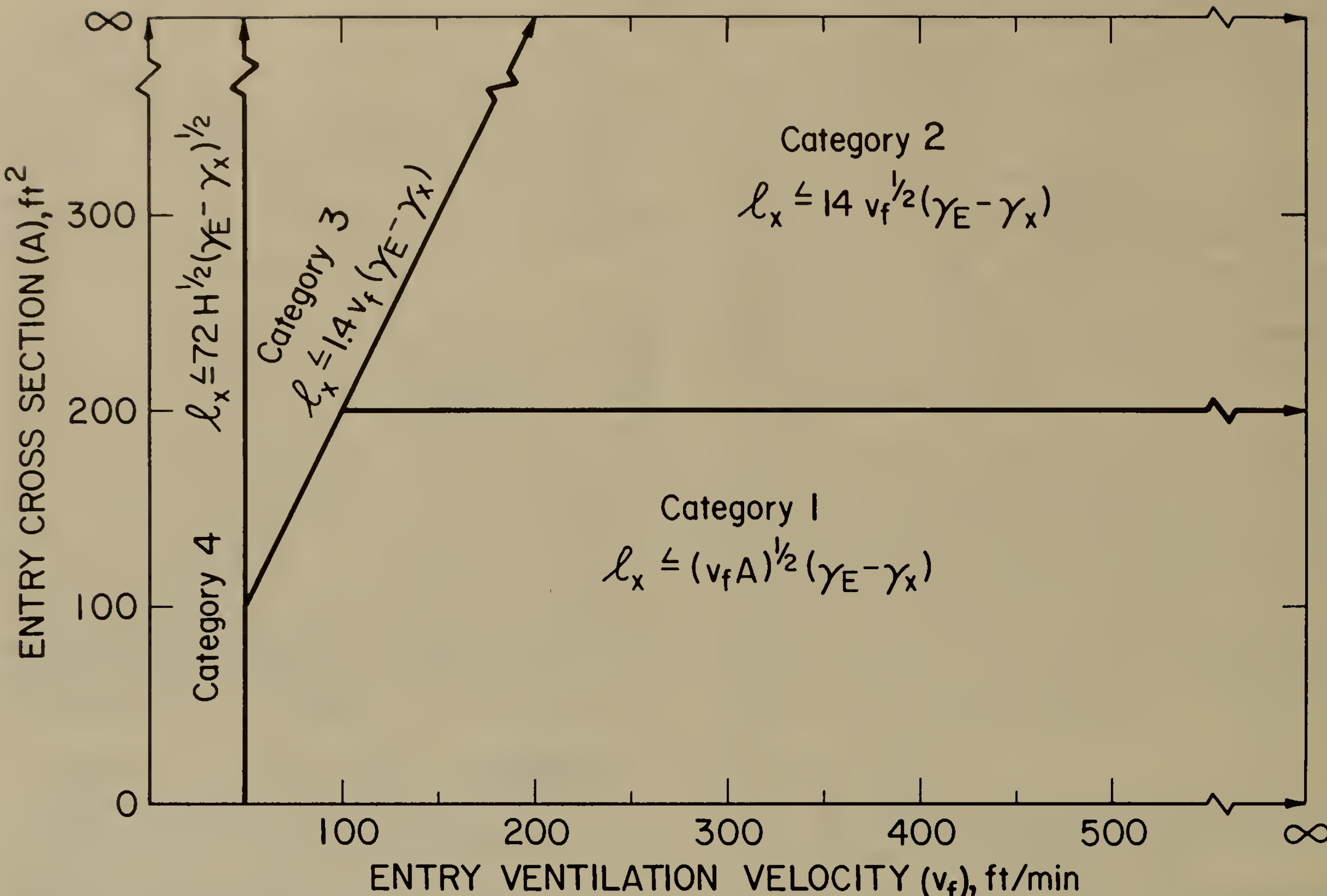

FIGURE 3. - Spacing categories and appropriate spacing equations for mine entries.

4. Primary combustible: coal; from table 1, K_{CO} for coal = 1.10.

5. Entry background CO level (X_o) = 4 ppm.

6. $(X_a - X_o)/K_{CO} = 14.5$.

7. From figure 2, at $(X_a - X_o)/K_{CO} = 14.5$, $\gamma_x = 19.0$.

8. Average entry ventilation velocity (v_f) = 300 ft/min.

9. Average entry cross section (A) = H × W = 6 × 20 = 120 ft^2.

10. The point of intersection of the v_f-vertical line and the A-horizontal line, in figure 3, falls within category 1. For category 1, the appropriate sensor spacing equation is

$$\ell_x \leq (v_f A)^{1/2} \ (\gamma_E - \gamma_x)$$

$$\leq 190\ (30.4 - 19.0)$$

$$\leq 2{,}166 \text{ ft}.$$

This is the maximum recommended spacing between these sensors in this entry.

VERTICAL PLACEMENT

Because the hot gases from a fire will rise owing to buoyancy forces, combustion products will initially be stratified near the roof of an entry. As this stratified gas layer moves away from the fire, the resultant cooling and dilution will eventually produce a well-mixed flow of combustion products. Data from full-scale fires indicate that some degree of stratification can exist at distances of

hundreds of feet from the source of the fire.

Because of this effect, POC fire sensors should be located at a vertical distance from the entry roof that does not exceed 25% of the average entry height. For example, in an entry with a height of 6 ft, the maximum distance from the roof at which a POC sensor should be located is 1-1/2 ft. This refers to the location of the actual sampling intake of the detector used.

LATERAL PLACEMENT

In general, the point of origin of a fire is quite unpredictable. It may occur along the floor, ribs, or roof of an entry. In order to provide optimum protection, it is recommended that the fire sensors be located within 2 ft of the approximate midpoint of the entry.

For entries in which the point of origin of the fire can be better estimated (such as a belt entry), the sensors should be located in such a manner that they provide for the estimated best coverage of that entry. As an example, in a belt entry where the conveyor is on one side of the entry, it would be more judicious to locate the sensors above the centerline of the belt conveyor than to locate them in the middle of the entry.

FIRE DETECTION CRITERION

The basis for development of POC fire sensor spacing guidelines is the performance of a series of ideal 160° F heat sensors spaced at intervals of 10 ft within an underground mine entry. The estimated alarm times for this ideal thermal system define the detection criterion for POC fire sensors: Any POC fire-sensing system must have an alarm time less than or equal to this thermal alarm time.

The data obtained from full-scale mine fires[3] are used in the following paragraphs to estimate the fire sizes and alarm actuation times for the ideal 160° F heat sensors with spacing intervals of 10 ft.

Temperature data obtained during full-scale mine fires[4] indicate that the maximum downstream air temperature at a distance ℓ is related to the heat release rate of the fire, the entry ventilation velocity, and the entry dimensions by the equation

$$\dot{Q}_f = \rho\ c_p\ v_f A\ \frac{T_a - T_o}{9}\ (0.305\ \ell)^{1.75\ H/W}, \quad (1)$$

where T_a = maximum downstream air temperature, °F, at a distance ℓ downstream;

T_o = ambient air temperature, °F;

$\dot{Q}_f$ = fire heat release rate, Btu/min;

ρ = density of air = 0.075 lb/ft^3;

c_p = heat capacity of air = 0.26 Btu/(lb·°F);

v_f = ventilating air velocity, ft/min;

ℓ = distance from fire to downstream thermal sensor, ft;

H = entry height, ft;

W = entry width, ft;

and A = entry cross-sectional area (H × W), ft^2.

Using equation 1, the detection criterion is developed as follows. The maximum downstream distance is set equal to 10 ft; T_a equals 160° F; and T_o is assumed to have a value of 65° F. From

[3] Second and third works cited in footnote 2.

[4] Second work cited in footnote 2.

equation 1, the fire size at which the maximum air temperature reaches 160° F at a distance of 10 ft downstream becomes

$$\dot{Q}_T = 0.206\ v_f A\ (3.05)^{1.75\ H/W}, \quad (2)$$

where the subscript T denotes the fire size at the time of thermal alarm.

From data previously reported,[5] the rate at which the fire size increases, from the instant of flaming ignition, is given by

$$\dot{Q}_f = 4.0 \times 10^{-4}\ v_f^2 t^2, \quad (3)$$

where t is the time, in minutes.

By setting $\dot{Q}_f = \dot{Q}_T$ and solving for t in equation 3, the time to thermal alarm (t_T) can be determined:

$$t_T = 22.7\ (3.05)^{0.875\ H/W}\ \frac{(v_f A)^{1/2}}{v_f}. \quad (4)$$

Equations 2 and 4 define the approximate fire size at time of alarm and the resultant alarm time for a series of ideal 160° F heat sensors spaced at intervals of 10 ft. Further, the 10-ft spacing is constant, independent of the entry dimensions. In essence, then, equations 2 and 4 define the fire size at alarm and the alarm time for ideal 160° F heat sensors within any entry; and for known values of H, W, and v_f, the actual fire sizes and times can be calculated.

The criterion can be stated as follows: Any fire detection system installed within an entry of height H, width W, and ventilation velocity v_f must respond (alarm) in a time less than or equal to the time required for a series of ideal 160° F heat sensors spaced at 10-ft intervals to respond if located in the same entry. This thermal response time, which serves as the basis for comparison, is defined in equation 4.

Since t_T is a function of H and W, it is convenient to define a parameter, γ_E, called the entry parameter, as

$$\gamma_E = 22.7\ (3.05)^{0.875\ H/W}. \quad (5)$$

This parameter is plotted in figure 1 as a function of H/W.

With this defined entry parameter, t_T can be rewritten as

$$t_T = \gamma_E\ \frac{(v_f A)^{1/2}}{v_f}. \quad (6)$$

The following sections apply this detection criterion to the development of spacing guidelines for POC fire sensors in underground mines. This criterion can also be used to define spacings for heat sensors with alarm thresholds other than the assumed 160° F, through the use of equation 1.

PRODUCTS OF COMBUSTION

The quantity of any combustion product will increase as the fire size increases. In a ventilated mine entry, the bulk average increase in concentration for some product (X) is equal to the rate of generation of that product divided by the volumetric ventilation rate (simple dilution). The equation that defines this bulk average concentration increase is

$$X_T - X_o = \frac{Y_x\ \frac{\dot{Q}_f}{H_c}}{v_f A}, \quad (7)$$

where X_T = total concentration of product X;

X_o = ambient background concentration of product X;

Y_x = quantity of X produced per mass of combustible consumed (the yield of X);

and H_c = heat of combustion of the material burning.

When X_T equals the alarm threshold concentration (X_a), equation 7 can be

[5] Second work cited in footnote 2.

rearranged to obtain the approximate fire size ($\dot{Q}_x$) required to produce X_a:

$$\dot{Q}_x = v_f A \frac{H_c}{Y_x} (X_a - X_o). \tag{8}$$

By setting $\dot{Q}_f = \dot{Q}_x$ in equation 3, the time at which the POC concentration will reach the alarm threshold (t_x) can be determined.

$$t_x = 50.0 \left(\frac{H_c}{Y_x} (X_a - X_o) \right)^{1/2} \frac{(v_f A)^{1/2}}{v_f}. \tag{9}$$

By setting the ratio Y_x/H_c equal to 100 K_x, equation 9 becomes

$$t_x = 5.0 \left(\frac{(X_a - X_o)}{K_x} \right)^{1/2} \frac{(v_f A)^{1/2}}{v_f}. \tag{10}$$

The parameter K_x is defined as the production constant for product X and is also a function of the combustible that is burning. K_x-values for the products CO, CO_2, and smoke particles (SMP) have been obtained from full-scale and intermediate-scale fire tests for both coal and wood[6] during flaming combustion and are listed in table 1.

A second global parameter, γ_x, called the POC parameter, is defined by the expression

$$\gamma_x = 5.0 \left(\frac{X_a - X_o}{K_x} \right)^{1/2}; \tag{11}$$

γ_x is plotted in figure 2 as a function of $(X_a - X_o)/K_x$. When this parameter is inserted into equation 10, t_x becomes

$$t_x = \gamma_x \frac{(v_f A)^{1/2}}{v_f}. \tag{12}$$

In order to satisfy the criterion of equation 6, the time available (t_D) for the transport of the alarm threshold concentration level of product X from the fire origin to a sensor site is

$$t_D = t_T - t_x, \tag{13}$$

which, in terms of the two parameters, γ_E and γ_x, becomes

$$t_D = \frac{(v_f A)^{1/2}}{v_f} (\gamma_E - \gamma_x). \tag{14}$$

SENSOR SPACING CATEGORIES

Because the entry cross sections of underground mines and the imposed entry ventilation rates can vary greatly, a single equation cannot be applied equitably for the spacing of all underground mine fire sensors. For this reason, the spacing guidelines are subdivided into four distinct categories of entry cross sections and ventilation flows. (These categories are shown in figure 3.)

CATEGORY 1 MINE ENTRIES

For any mine entry in which the entry cross section is ≤ 200 ft^2, the entry ventilation flow is >50 ft/min, and the ratio A/v_f is ≤ 2.0 ft·min, the maximum sensor spacing is equal to

$$\ell_x \leq v_f t_D = (v_f A)^{1/2} (\gamma_E - \gamma_x), \tag{15}$$

where it is assumed that the combustion products are convected from the fire origin to the sensor site at a velocity equal to the average ventilation velocity in that entry.

CATEGORY 2 MINE ENTRIES

For any mine entry in which the entry cross section exceeds 200 ft^2 and the ratio A/v_f is ≤ 2.0 ft·min, t_D can be no greater than

$$t_D \leq (200/v_f)^{1/2} (\gamma_E - \gamma_x), \tag{16}$$

and the maximum sensor spacing no greater than

$$\ell_x \leq 14\ v_f^{1/2} (\gamma_E - \gamma_x). \tag{17}$$

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[6]First and second works cited in footnote 2.

CATEGORY 3 MINE ENTRIES

For any mine in which the ratio A/v_f is >2.0 ft•min, regardless of entry cross section, t_D can be no greater than

$$t_D \leq (2)^{1/2} \; (\gamma_E - \gamma_x) = 1.4 \; (\gamma_E - \gamma_x), \quad (18)$$

and the maximum sensor spacing no greater than

$$\ell_x \leq 1.4 \; v_f \; (\gamma_E - \gamma_x). \quad (19)$$

CATEGORY 4 MINE ENTRIES

For any mine entry in which the ventilation velocity is <50 ft/min, the maximum sensor spacing is defined by

$$\ell_x \leq 72 \; H^{1/2} \; (\gamma_E - \gamma_x)^{1/2}. \quad (20)$$

This expression is based upon a no-flow approximation, and its derivation can be found in appendix A.

SAMPLING-TYPE FIRE DETECTORS

The guidelines developed in the previous sections apply directly to spot-type detectors, which may be located in fixed positions corresponding to the spacing recommended for a given entry. Consequently, for an entry of length ℓ_E, with a sensor requiring spacing ℓ_x in that entry, the number of sensors (n) would equal ℓ_E/ℓ_x.

An alternative to this type of system is a sampling-type fire detector. Instead of having sensors located at fixed positions, a sampling-type detector has sampling ports connected to one single sensor via hollow-core tubing. Pumps are used to continuously pull samples of air from the sampling port locations to the detector where the samples are analyzed for combustion products.

For this type of detector, the spacing guidelines cannot be applied directly to location of the sampling ports, because of the additional time that is required for the system to respond, owing to tube traveltimes and sequencing times at the detector station. In order to determine the required spacings for sampling ports for this type of sensor, the additional times must be included in the overall response time of the system (t_s).

For a sampling-type detector, it is usually prudent to determine the number of sample ports (n) required to protect an entry of length ℓ_E. To determine n, the time response of a sampling-type detector can be written as a function of n and other known variables. The time response of a sampling-type detector is given by

$$t_s = t_D + t_x + t_\ell + t_{seq}, \quad (21)$$

where t_D = transport time of combustion product between sample ports;

t_x = time at which POC concentration will reach the alarm threshold level (previously defined in equation 12);

t_ℓ = sample traveltime through the longest sampling tube;[7]

and t_{seq} = the time required by the detector to sequence through all sampling tubes, which is equal to the number of tubes (n) times the sampling time per tube (t_{samp}).

The total response time must be less than or equal to t_T (equation 6) in order to satisfy the detection criterion. Since the sample port spacing (ℓ_s) equals ℓ_E/n, the following equation must be satisfied:

$$\ell_E/n + v_f \; (t_\ell + n t_{samp}) \leq \ell_x, \quad (22)$$

where ℓ_x is the recommended spacing for category 1, 2, or 3 mine entries.

Solving equation 22 for n yields

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[7] See appendix B for derivation of t_ℓ.

$$n = \frac{(\ell_x - v_f t_\ell) - \sqrt{(\ell_x - v_f t_\ell)^2 - 4\,\ell_E\, t_{samp}\, v_f}}{2t_{samp}\, v_f} \tag{23}$$

and is the defining equation for category 1, 2, or 3 mine entries.

For a category 4 mine entry ($v_f \leq 50$ ft/min), the resulting equation is[8]

$$\frac{\ell_E}{n} < 60H^{1/2}\,[1.4\,(\gamma_E - \gamma_x) - (t_\ell + nt_{samp})]^{1/2}. \tag{24}$$

Equations 23 and 24 can be used to determine the required number of sample ports (n) for an entry of length ℓ_E. The spacing between sample ports (ℓ_s) is then equal to ℓ_E/n. Expressions for the tube traveltimes (t_ℓ) to be used in these two equations can be found in appendix B.

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[8]See appendix A.

APPENDIX A.--DERIVATION OF LOW-FLOW SENSOR SPACINGS

From data available in the literature,[1] empirical expressions were derived for the maximum temperature difference ($T_{max}-T_o$) and maximum gas velocity (v_{max}) near the roof, as a function of roof height (H), fire heat release rate ($\dot{Q}_f$), and radial distance (r) from the fire origin, for fires developing under static (no-flow) conditions. The respective expressions for $T_{max}-T_o$ and v_{max} are

$$T_{max} - T_o = \frac{4.74\ (\dot{Q}_f/r)^{2/3}}{H} \qquad \text{(A-1)}$$

and $$v_{max} = 15.0\ \dot{Q}_f^{1/3}\ H^{1/2}/r^{5/6}, \qquad \text{(A-2)}$$

where T_{max} and T_o are in ° F;

v_{max} is in ft/min;

$\dot{Q}_f$ is in Btu/min;

and H and r are in ft.

These two expressions apply to radially expanding hot product gases, and, for a mine entry, hot gases can spread radially only until they reach the ribs of the entry. Once they reach the ribs, the hot gases will expand along the length of the entry, and at an increased rate. In view of this behavior, the following derivation for POC sensor spacings, using these radially expanding expressions, should be viewed as conservative estimates.

As before, the basis for comparison will be a series of ideal 160° F heat sensors spaced at intervals of 10 ft. Since the hot gases are free to expand radially under static conditions, the maximum distance they will travel before being detected will be one-half the spacing, or 5 ft. Using this value for r in equation A-1 and assuming T_o = 65° F, the fire size at which $T_{max} = T_a$ = 160° F can be obtained. It is

$$\dot{Q}_T = 448.6\ H^{3/2}. \qquad \text{(A-3)}$$

Assuming that, under static conditions, the fire will grow at a rate less than or equal to the rate at the minimum velocity of v_f = 50 ft/min, equation 3[2] can be used to define the approximate fire growth rate:

$$\dot{Q}_f = t^2. \qquad \text{(A-4)}$$

When $\dot{Q}_f = \dot{Q}_T$, the approximate time to thermal alarm can be obtained:

$$t_T = 21.18\ H^{3/4}. \qquad \text{(A-5)}$$

By substituting equation A-4 into equation A-2, the velocity (v_{max}) at any radial distance (r) becomes a function of time. By taking the integral average of v_{max}, from t = 0 to t = t_T, the average velocity (v_{avg}) at any radial distance (r) can be obtained; that is,

$$v_{avg} = \frac{\int_0^{t_T} v_{max}(t)\ dt}{\int_0^{t_T} dt} = \frac{68.9\ H}{r^{5/6}}. \qquad \text{(A-6)}$$

Equation A-6 defines the average velocity at any radial distance (r) during the thermal alarm time interval (t_T). The average gas velocity (v_o) that the hot gases will have in traversing a fixed distance (r_o) is the integral average of v_{avg} from r = o to r = r_o; that is,

$$v_o = \frac{\int_0^{r_o} v_{avg}(r)\ dr}{\int_0^{r_o} dr} = \frac{413.4\ H}{r_o^{5/6}}. \qquad \text{(A-7)}$$

For ventilation velocities of 50 ft/min or less, the quantity A/v_f will be limited to a maximum value of 2, and from equation 18, the maximum transport time

[1] Alpert, R. L. Calculation of Response Time of Ceiling-Mounted Fire Detectors. Fire Technol., v. 8, No. 3, August 1979, pp. 181-195.

[2] Equation numbers without the A-prefix refer to equations occurring in the main text.

(t_D) is defined in terms of the parameters γ_E and γ_x by

$$t_D = 1.4\ (\gamma_E - \gamma_x). \qquad \text{(A-8)}$$

For a POC fire sensor located at a distance r_o from the fire, the average velocity (v_o) required to traverse that distance in a time t_D is

$$v_o = \frac{r_o}{t_D} = \frac{r_o}{1.4\ (\gamma_E - \gamma_x)}. \qquad \text{(A-9)}$$

Since v_o from equation A-7 must equal v_o defined by equation A-9, the following expression can be obtained for r_o:

$$r_o = 32.12\ [H(\gamma_E - \gamma_x)]^{6/11}. \qquad \text{(A-10)}$$

Equation A-10 defines the maximum radial expansion distance for a sensor (defined by γ_x) installed within an entry defined by H and γ_E. Since the product gases expand both upstream and downstream, two sensors spaced at an interval of 2 r_o would be expected to respond at the same time to a fire located midway between them. Consequently, the maximum sensor spacing is defined by

$$\ell_x \leq 2r_o = 64.24\ [H\ (\gamma_E - \gamma_x)]^{6/11}. \qquad \text{(A-11)}$$

Assuming a minimum entry height of ~3 ft and reasonable values of $\gamma_E - \gamma_x$ lying between 5 and 30, the quantity H ($\gamma_E - \gamma_x$) can be expected to lie between 15 and 90, and equation A-11 can be approximated by a more convenient expression given by

$$\ell_x \leq 72\ [H(\gamma_E - \gamma_x)]^{1/2}. \qquad \text{(A-12)}$$

If the ratio of equation A-11 to equation A-12 is taken, it can be shown that, for values of $H(\gamma_E - \gamma_x) < 12.3$, equation A-11 will require a somewhat smaller spacing than that required by equation A-12. For values of $H(\gamma_E - \gamma_x) > 12.3$, the spacing required by A-12 will always be less than the spacing required by A-11; thus, equation A-12 should be viewed as a conservative approximation to the derived spacing. For example, with $\gamma_x = 15.1$ (a CO sensor for 10 ppm above ambient) in an entry of H = 6 ft and W = 20 ft ($\gamma_E = 30.4$), equation A-12 would require a spacing of 690 ft or less, while equation A-11 would require a spacing of 756 ft or less, a spacing about 10% larger.

Consequently, for <u>any</u> entry in which the ventilation velocity is ≤50 ft/min, equation A-12 should be used to determine the appropriate spacing for a POC fire sensor.

For a sampling-type fire detector, the maximum available transport time (t_D) is given by

$$t_D = 1.4\ (\gamma_E - \gamma_x) - (t_\ell + nt_{samp}), \qquad \text{(A-13)}$$

and the average velocity in traversing some distance r_o by

$$v_o = \frac{r_o}{1.4\ (\gamma_E - \gamma_x) - (t_\ell + nt_{samp})}. \qquad \text{(A-14)}$$

Setting equation A-14 equal to equation A-7 and solving for r_o yields

$$r_o = 27\ H^{6/11}\ [1.4\ (\gamma_E - \gamma_x) - (t_\ell + nt_{samp})]^{6/11}. \qquad \text{(A-15)}$$

As before, the sample port spacing (ℓ_s) should be equal to 2 r_o, and, applying the same approximation as before (equation A-12), the expression for the sample port spacing becomes

$$\ell_s \leq 60\ H^{1/2}\ [1.4\ (\gamma_E - \gamma_x) - (t_\ell + nt_{samp})]^{1/2}. \qquad \text{(A-16)}$$

For an entry of length, ℓ_E, the sample port spacing equals ℓ_E/n, where n is the number of sample ports spaced at equal intervals.

APPENDIX B.--DERIVATION OF TUBE TRAVELIMES

In general, the flow through each tube of a sampling-type detector should be laminar. In order to satisfy this constraint, the Reynolds number should be less than or equal to 1,800. Then,

$$Re = \frac{\rho \ell_t \; d_s}{12 \; t_\ell \eta} \leqslant 1,800, \qquad \text{(B-1)}$$

where ρ = density of air = 0.075 lb/ft^3;

η = kinematic viscosity = 7.26 × 10^{-4} lb/(ft·min);

ℓ_t = sample tube length, ft;

d_s = tube inside diameter, in;

and t_ℓ = tube traveltime, min.

Solving equation B-1 for t_ℓ yields

$$t_\ell \geqslant 4.78 \times 10^{-3} \; \ell_t \; d_s. \qquad \text{(B-2)}$$

For sampling-type gas detectors (CO, CO_2) there is an additional constraint on the size of tubing (d_s) that can be used for a given length (ℓ_t). This constraint is related to the pumping requirements for the system,[1] and is given by

$$d_s \geqslant 0.02 \; \ell_t{}^{1/3}. \qquad \text{(B-3)}$$

Substituting this expression into equation B-2 yields

$$t_\ell \geqslant 9.56 \times 10^{-5} \; \ell_t{}^{4/3}, \qquad \text{(B-4)}$$

which defines the tube traveltime solely in terms of the tube length. Clearly, when $\ell_t = \ell_{max}$, the maximum tube length in the system, (t_ℓ) will have its greatest value. Then the maximum value of t_ℓ is given by

$$t_\ell \geqslant 9.56 \times 10^{-5} \; \ell_{max}{}^{4/3}. \qquad \text{(B-5)}$$

This is the expression to be used in equation 22 and 23[2] for a sampling-type gas detector.

For a sampling-type smoke detector (SMP) there is a different constraint on the size of tubing (d_s) that can be used for a given length (ℓ_t). This constraint is related to the losses of particles that can occur within a tube as the smoke is transported from the sample port to the detector.[3] The constraint is

$$d_s \geqslant 1.95 \times 10^{-4} \; \ell_t. \qquad \text{(B-6)}$$

When $\ell_t = \ell_{max}$, the maximum tube traveltime is

$$t_\ell \geqslant 9.32 \times 10^{-7} \; \ell_{max}{}^2. \qquad \text{(B-7)}$$

This is the expression to be used for t_ℓ in equations 22 and 23 for a sampling-type smoke detector.

Both equations B-5 and B-7 indicate that the larger the value for ℓ_{max}, the longer the tube traveltime (t_ℓ). Further, equations B-3 and B-6 indicate that as ℓ_t increases, larger tube diameters (d_s) will be required. The values of ℓ_{max} and other sample tube lengths (ℓ_t) depend upon the location of the detector station relative to the sample ports. The best location of the detector station is central to the location of the sample ports. For sample ports spaced at equal intervals (ℓ_s) along an entry of length ℓ_E, and with the detector station located centrally with respect to the sample ports, the maximum tube length (ℓ_{max}) is given by

$$\ell_{max} = \frac{\ell_E - \ell_s}{2}. \qquad \text{(B-8)}$$

Since $\ell_s = \ell_E/n$, ℓ_{max} can be rewritten as

$$\ell_{max} = \left(\frac{n-1}{2n}\right)\ell_E. \qquad \text{(B-9)}$$

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[1] Litton, C. D. Design Criteria for Rapid Response of Pneumatic Monitoring Systems. BuMines IC 8912, in press; for information, contact C. D. Litton, Bureau of Mines, Pittsburgh, Pa.

[2] Equation numbers without the B-prefix refer to equations occurring in the main text.

[3] Work cited in footnote 1.

In general, it is sufficient to approximate the above equation by

$$\ell_{max} = 1/2\ \ell_E. \tag{B-10}$$

As a result, for applications in which the detector station can be located centrally with respect to the sample ports, the maximum tube traveltimes can be rewritten as

$$t_\ell \geqslant 3.79 \times 10^{-5}\ (\ell_E)^{4/3} \tag{B-11}$$

for sampling-type CO or CO_2 detectors, and as

$$t_\ell \geqslant 2.33 \times 10^{-7}\ \ell_E{}^2, \tag{B-12}$$

for sampling-type SMP detectors.

For applications in which the detector station cannot be centrally located, the anticipated location of the detector relative to the farthest sample port will define ℓ_{max}, and t_ℓ can be determined from either equation B-5 or B-7.

It is important to note that all tubes must satisfy the size constraints defined by either equation B-3 or B-6.

☆U.S. GOVERNMENT PRINTING OFFICE: 1983-605-015/10

INT.-BU.OF MINES,PGH.,PA. 26626